

Estimate of CP Violation for the LBNE Project and δ_{CP}

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Abstract

Measurements of CP violation (CPV) and the basic δ_{CP} parameter are the goals of the LBNE Project, which is being planned. Using the expected energy and baseline parameters for the LBNE Project, CPV and the dependence of CPV on δ_{CP} are estimated, to help in the planning of this project.

1 Introduction

For several decades there have been many experimental and theoretical studies of CP violation (CPV). Recently we have studied time reversal violation (TRV)[1] and CPV[2] for neutrino oscillations in matter, using parameters of current neutrino oscillation experiments, MiniBooNE[3], JHF-Kamioka [4], MINOS[5], and CHOOZ[6]. See Refs.[1],[2] for details and references to earlier work on T and CP. When neutrino beams move through matter the CPT theorem is not valid (see. e.g., Ref[7]); therefore TRV and CPV are not directly related. There have been many other studies of CP asymmetries in weak decays: see Ref[8] for a recent study of \bar{B} radiative decay with references to earlier work on CP violation in various weak decays. Also, in addition to the baseline, energy, and the matter density, there are a number of parameters associated with neutrino oscillations, as will be seen in our discussion of CP violation below. There have been a number of studies of

these parameters; see, e.g., Refs[9, 10], which contain references to earlier related publications.

In our present work we study CPV using the baseline and energies expected for the future LBNE Project[11]. See Ref[12] for a detailed report on the project, and the recent discussion of the LBNE parameters[13], with a baseline $L=1300$ km and energies in the range $E=0.5-12$ GeV. We use the expected baseline of 1300 km and five possible energies. There have also been a number of studies of matter effects for the LBNE Project[12]. See Davoudiasl *et al*[14] and Gonzalez-Garcia *et al*[15] for recent studies of matter effects and various parameters important for the baseline L expected in the LBNE Project, and references to earlier studies for the LBNE Project.

One of the main objectives of this future project is to measure the δ_{CP} parameter. In the present work we calculate CPV as a function of δ_{CP} for parameters being studied for the LBNE Project, to help in the design of this future experiment. In order to determine δ_{CP} via neutrino oscillations one also needs the angles θ_{12}, θ_{23} , which are well-known, and the angle θ_{13} , which is being studied by a number of experiments: T2K[16], Daya Bay[17, 18] Double Chooz[19, 20], and RENO[21]. A very recent result from the Daya Bay project[22], which is consistent within errors of the recent RENO[21] result, finds that $s_{13} \simeq 0.15$, which we use in the present study.

As pointed out above, an essential aspect of the determination of CPV, as well as TRV and CPTV is the interaction of neutrinos with matter as they travel along the baseline. See, e.g., Refs[23, 24, 25, 26]. Since this was discussed in detail in Ref[2], some details are not given in the present work. In the present work we use the notation and formalism of Jacobson and Ohlsson[7], who studied possible matter effects for CPT violation.

CP violation in the $a - b$ sector is given by the transition probability, denoted by $\mathcal{P}(\nu_a \rightarrow \nu_b)$, for a neutrino of flavor a to convert to a neutrino of flavor b ; and similarly for antineutrinos $\bar{\nu}_a, \bar{\nu}_b$. The CPV (note that the C operator changes a particle to its antiparticle) is defined as

$$\Delta\mathcal{P}_{ab}^{CP} = \mathcal{P}(\nu_a \rightarrow \nu_b) - \mathcal{P}(\bar{\nu}_a \rightarrow \bar{\nu}_b) . \quad (1)$$

In our present work we study $\mathcal{P}(\nu_\mu \rightarrow \nu_e)$ and $\mathcal{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, since the neutrino beams at LBNE are muon or anti-muon neutrinos.

As discussed above, there are four angles in the matrix relating a neutrino with flavor to neutrinos with mass, the basis for neutrino oscillations. The two angles under current study are δ_{CP} and θ_{13} . In order for the LBNE proposed project to be successful in determining δ_{CP} , θ_{13} must be known. One might expect that the experiments Daya Bay, RENO, and Double Chooz could not achieve their goal of determining θ_{13} to an accuracy of 1% without knowing δ_{CP} . As is discussed below, fortunately, this is not the case.

2 CP Violation $\Delta\mathcal{P}_{\mu e}^{CP}$

We use the time evolution matrix in flavor space to derive CPV. The neutrino state at time $= t$ is obtained from the state at time $= t_0$ from the matrix, $S_f(t, t_0)$, for neutrino flavor f . See Ref[7] for a detailed derivation of $S_f(t, t_0)$.

Using the notation S_{ab} and \bar{S}_{ab} for the flavor a, b matrix element for neutrinos and antineutrinos, the CPV probability is given by

$$\begin{aligned}\Delta\mathcal{P}_{\mu e}^{CP} &= \mathcal{P}(\nu_\mu \rightarrow \nu_e) - \mathcal{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \\ &= |S_{12}|^2 - |\bar{S}_{12}|^2 \\ S_{12} &= c_{23}\beta - is_{23}ae^{-i\delta_{CP}}A \\ \bar{S}_{12} &= c_{23}\bar{\beta} - is_{23}ae^{i\delta_{CP}}\bar{A}.\end{aligned}\tag{2}$$

The parameters in Eq(2) are

$$a = s_{13}(\Delta - s_{12}^2\delta)\tag{3}$$

$$\delta = \delta m_{12}^2/(2E)\tag{4}$$

$$\Delta = \delta m_{13}^2/(2E)\tag{5}$$

$$A \simeq f(t)I_\alpha^*\tag{6}$$

$$I_\alpha^* = \int_0^t dt' \alpha^*(t')f(t')\tag{7}$$

$$\alpha(t) = \cos\omega t - i\sin 2\theta \sin\omega t\tag{8}$$

$$f(t) = e^{-i\bar{\Delta}t}\tag{9}$$

$$2\omega = \sqrt{\delta^2 + V^2 - 2\delta V \cos(2\theta_{12})}\tag{10}$$

$$\beta = -i\sin 2\theta \sin\omega L\tag{11}$$

$$\bar{\Delta} = \Delta - (V + \delta)/2\tag{12}$$

$$\sin 2\theta = s_{12}c_{12}\frac{\delta}{\omega},\tag{13}$$

where the neutrino mass differences are $\delta m_{12}^2 = 7.6 \times 10^{-5}(eV)^2$ and $\delta m_{13}^2 = 2.4 \times 10^{-3}(eV)^2$. The neutrino-matter potential $V = \sqrt{2}G_F n_e$, where G_F is the universal weak interaction Fermi constant, and n_e is the density of electrons in matter. Using the matter density $\rho=3$ gm/cc, which is the expected average density for LBNE experiment, $V = 1.13 \times 10^{-13}$ eV. We use $s_{12} = 0.56$ and $s_{23} = 0.707$; and $s_{13} = 0.15$, as recently found in the anti-neutrino disappearance Daya Bay[22] and RENO[21] experiments. Note that for antineutrinos $\delta_{CP} \rightarrow -\delta_{CP}$. $\bar{\beta} = \beta(V \rightarrow -V)$ and $\bar{A} = A(V \rightarrow -V)$.

For example,
 $2\bar{\omega} = \sqrt{\delta^2 + V^2 + 2\delta V \cos(2\theta_{12})}$ and $\bar{\bar{\Delta}} = \Delta + (V - \delta)/2$.
 Using conservation of probability[7], $|A|^2 = |\bar{A}|^2$, from Eq(2)

$$\Delta\mathcal{P}_{\mu e}^{CP} = c_{23}^2(|\beta|^2 - |\bar{\beta}|^2) - 2c_{23}s_{23}a\text{Im}[\beta e^{-i\delta_{CP}}A^* - e^{i\delta_{CP}}\bar{\beta}\bar{A}^*]. \quad (14)$$

From Eqs(2-14) it follows that $\Delta\mathcal{P}_{\mu e}^{CP}$ as a function of energy E and δ_{CP} is

$$\begin{aligned} \Delta\mathcal{P}_{\mu e}^{CP}(E, \delta_{CP}) = & c_{23}^2 s_{12}^2 c_{12}^2 \delta^2 \left(\frac{s^2}{\omega^2} - \frac{\bar{s}^2}{\bar{\omega}^2} \right) + 2c_{23}s_{23}s_{12}c_{12}s_{13}\delta(\Delta - \delta s_{12}^2) \\ & \left(\sin\delta_{CP} \left(\frac{s}{\omega} (c - \cos\bar{\Delta}L) \frac{\bar{\Delta} - \omega \cos 2\theta}{\bar{\Delta}^2 - \omega^2} + \frac{\bar{s}}{\bar{\omega}} (\bar{c} - \cos\bar{\bar{\Delta}}L) \frac{\bar{\bar{\Delta}} - \bar{\omega} \cos 2\bar{\theta}}{\bar{\bar{\Delta}}^2 - \bar{\omega}^2} \right) \right. \\ & + \cos\delta_{CP} \left(\frac{s}{\omega(\bar{\Delta}^2 - \omega^2)} (\sin\bar{\Delta}L(\bar{\Delta} - \omega \cos(2\theta)) + s(\bar{\Delta} \cos(2\theta) - \omega)) \right. \\ & \left. \left. - \frac{\bar{s}}{\bar{\omega}(\bar{\bar{\Delta}}^2 - \bar{\omega}^2)} (\sin\bar{\bar{\Delta}}L(\bar{\bar{\Delta}} - \bar{\omega} \cos(2\bar{\theta})) + \bar{s}(\bar{\bar{\Delta}} \cos(2\bar{\theta}) - \bar{\omega})) \right) \right). \end{aligned} \quad (15)$$

As is clear from Eq(15), $\Delta\mathcal{P}_{\mu e}^{CP}(E, \delta_{CP})$ depends on the value of s_{13} as well as the known s_{12}, s_{23} . Fortunately, as shown in Ref[2] $\mathcal{P}(\nu_\mu \rightarrow \nu_e)$ and the anti-electron neutrino disappearance being studied at Daya Bay, RENO, and Double Chooz is almost independent of δ_{CP} , and we can use the value $s_{13} = .15$, consistent with Refs[22, 21].

We calculate $\Delta\mathcal{P}_{\mu e}^{CP}(E, \delta_{CP})$ for L=1300km, the expected baseline in the proposed LBNE project[13]. From the possible energy range E=0.5-12 GeV for the LBNE project[13] we estimate $\Delta\mathcal{P}_{\mu e}^{CP}(E, \delta_{CP})$ a function of δ_{CP} for energies within the expected range.

The dependence of on $\Delta\mathcal{P}_{\mu e}^{CP}(E, \delta_{CP})$ on δ_{CP} for L=1300km is estimated for LBNE energies E=1, 2, 3, 5, 10 GeV, as shown in Fig. 1.

3 Conclusions

In the LBNE Report[12] results of extensive studies have shown that future experiments can extend our knowledge of neutrino oscillations beyond present and planned experiments. Since there will be both ν_μ and $\bar{\nu}_\mu$ beams, the LBNE Project can test CPV.

We have estimated CP violation for the LBNE Project, with a baseline L=1300 km as a function of δ_{CP} for $\delta_{CP} = 0$ to $\pi/2$ for energies of 1, 2, 3, 5, and 10 GeV, as shown in Fig. 1. We found CPV over 3% with $\delta_{CP} = \pi/2$ for some energies, which the Project should be able to measure. For higher energies, E=5, 10 GeV, $\Delta\mathcal{P}_{\mu e}^{CP}$ is smaller than at lower energies, and would be

harder to measure. We find that even for $\delta_{CP} = 0$, for which CPV is entirely a matter effect, CPV probabilities of over 1% were found for $E = 1$ GeV, so the Project should be able to measure CPV for any expected values of δ_{CP} . Fortunately, the value of θ_{13} has been determined, which should enable the LBNE project attain the goal of measuring δ_{CP} .

We believe that our calculations should be useful in planning the future LBNE Project.

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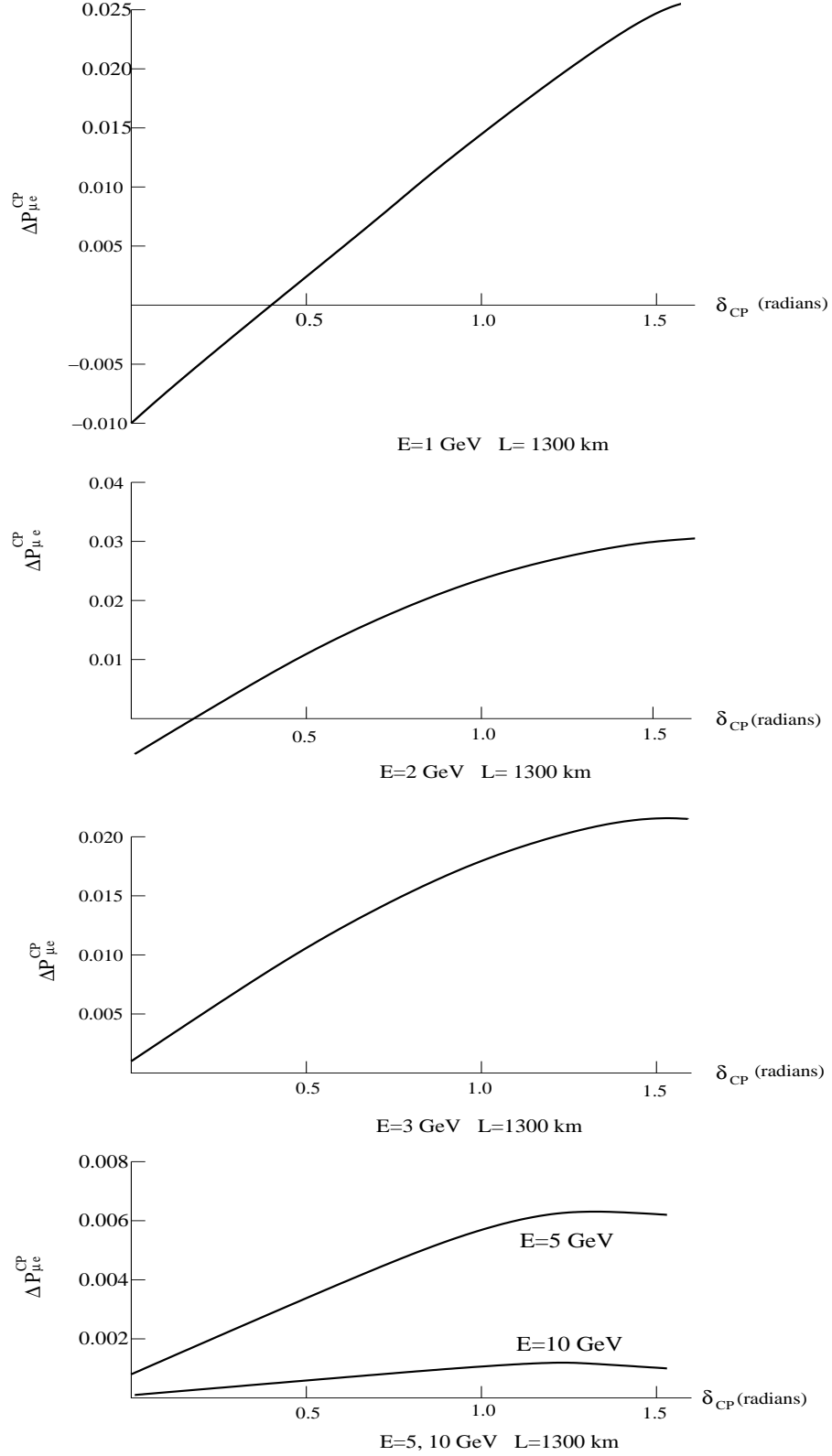


Figure 1: $\Delta \mathcal{P}(\nu_\mu \rightarrow \nu_e)$ as a function of δ_{CP} for expected LBNE L and E